

LONGITUDINAL COMPRESSING AND SHEARING PROPERTIES OF SILAGE CORN STALK IN NORTH CHINA PLAIN

华北平原青贮玉米秸秆纵向压缩剪切特性研究

Chen Meizhou¹⁾, Xu Guangfei¹⁾, Wei Maojian¹⁾, Song Zhicai¹⁾, Wang Wenjun¹⁾, Diao Peisong^{*1)} Teng Shaomin²⁾

¹⁾ School of Agricultural and Food Science, Shandong University of Technology, Zibo/China;

²⁾ Menoble Co., Ltd., Beijing/China

Tel: +86-13864306142; E-mail: dps2003@163.com

Corresponding author: Diao Peisong

DOI: <https://doi.org/10.35633/inmateh-65-05>

Keywords: silage corn stalks; compressing; longitudinal shearing; energy consumption

ABSTRACT

This paper aimed to optimize working quality and reduce energy consumption of the feeding and shearing device of the silage harvester by making a comprehensive analysis and experiment on the longitudinal compressing and shearing properties of the silage corn stalks. The main factors affecting the shearing energy consumption were obtained by compressing and shearing tests on internodes and nodes of silage corn stalk. The results of three-level and three-factor central combination experiments showed that the overall shearing energy consumption for nodes was much higher than that for internodes. Compressing the silage corn stalk to some extent before shearing at the loading direction of 0° and lower shearing speed was beneficial to saving energy.

摘要

本研究旨在通过对青贮玉米秸秆节间与节部的纵向压缩剪切性能分析，优化青贮收获机喂入与切碎装置的工作参数以降低作业能耗。根据青贮玉米秸秆的结构特性，分别对节间和节间压缩剪切试验，得出了影响剪切能量消耗的主要因素及水平。三因素三水平中心组合试验结果表明：秸秆节部的剪切能耗远大于节间的剪切能耗。以 0° 方向对青贮玉米秸秆进行压缩并以较低的剪切速率进行剪切有利于降低青贮玉米收获的能耗。

INTRODUCTION

Silage corn has been recognized as the highest quality roughage in the world, which has been used as basic feed for dairy cows and routine feed for beef cattle and sheep in countries with developed animal husbandry (Chattopadhyay *et al.*, 1999; Chen *et al.*, 2004). Silage corn accounts for about 8% of corn acreage in the United States and takes up about 80% of the corn planting area every year, among which France and Germany have the largest planting area, more than half of the European planting area (Chen *et al.*, 2012; USDA-NASS, 2017). In China, about 78% of China's total demand for corn is used for animal husbandry and it's expected that by the year 2020, the demand for corn used for animal husbandry will reach more than 89.2% (Lan *et al.*, 2019; Cheng *et al.*, 2019; Shinnors *et al.*, 2017). The silage corn cultivation in China is mainly concentrated in the Northeast, North China Plain and Southwest regions (Guo *et al.*, 2016; Li *et al.*, 2011; Liu *et al.*, 2014). The silage corn planting area in the North China Plain accounts for one-third of the country (Jiang *et al.*, 2017; Lan *et al.*, 2019). Summer corn is the main silage variety in the North China Plain and its stalk leaf yield is high and the annual yield is low. According to the National Planting Structure Adjustment Plan (2016-2020), the planting area of corn will be reduced by more than 3.33 million ha approximately and the area of silage corn will be increased to 1.67 million ha. That is to say, plenty of silage corn stalk as the main component of whole-plant silage corn need to be ensiled every year.

The purpose of silage harvesting is to cut up the silage corn stalk to a degree for easy storage and fermentation, therefore, the longitudinal shearing process is the most critical step in silage harvesting. The silage corn stalk needs to be compressed by a feeding device of silage harvester before shearing. Consequently, the variation in the longitudinal shearing properties of silage corn stalk under different compressing conditions needs to be known to understand the behavior of the material with different operations. In this paper, the compressing and shearing tests were conducted for silage corn stalks to understand the longitudinal shearing characteristics properties of silage corn stalk after compressing. This study was focused on determining the shearing energy of silage corn stalk according to various compressing rates, loading

direction and shearing speed. The purpose is to provide a scientific basis for optimizing the feeding and cutting mechanism of the silage harvester with high efficiency and low energy consumption.

MATERIALS AND METHODS

This study is based on the existing feeding and cutting device of the silage harvester. During the silage harvest, the corn stalks may enter the feeding device at any angle. After being grabbed and compressed under the action of the toothed feeding roller blades, the corn stalks are cut up by the moving blades mounted on a rotating roller of the cutting device (Lu et al., 2018). Its operating process is shown in Fig. 1.

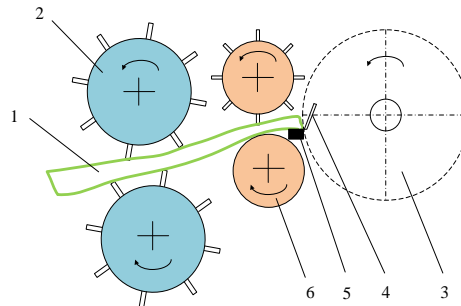


Fig. 1 - Feeding and shearing process of the silage harvester
 1. Silage corn; 2. Toothed feeding roller; 3. Cutting device; 4. Moving blade; 5. Stationary blade; 6. Smooth feeding roller

Therefore, we firstly compressed the internodes and nodes respectively to investigate their compressing properties and obtained the range of loading direction and compressing rate affecting the shearing effect. Secondly, the compressed internodes and nodes were sheared to investigate the shearing properties and the range of shearing speeds were obtained. Finally, the Box-Behnken central composite experiments were carried out to obtain the best work parameters for lower shearing energy consumption.

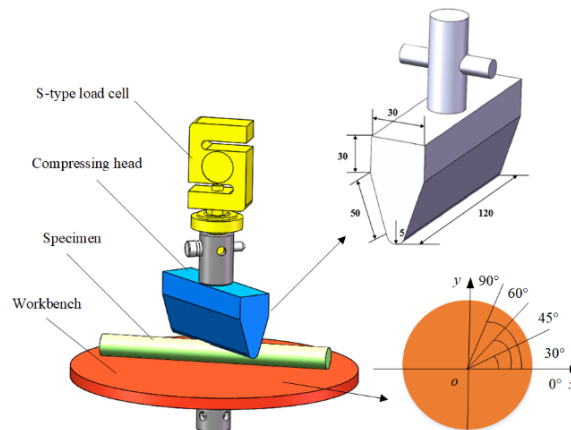


Fig. 2 - Stalk compressing schematic diagram

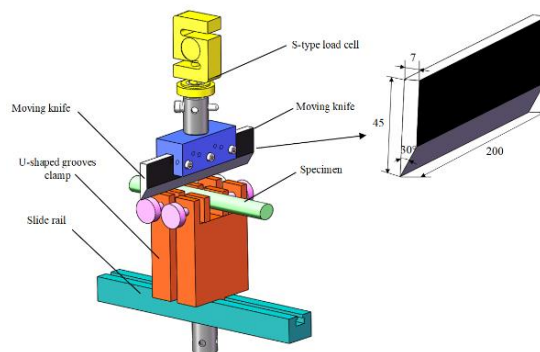


Fig. 3 - Stalk shearing schematic diagram

Compressing process: A compressing head was used to load in the vertical direction to simulate the feeding and compressing of the feeding roller blades with the test specimen axis consistent with the marked direction (0°, 45° and 90°) of workbench (Fig.2) (McRandal et al., 1980; Wang et al., 2019).

Shearing process: The crosscutting shear mode is adopted for the static shearing characteristic study. The custom moving blade fixed by a custom fixture was mounted to a beam of the UTM with a strain-gage load cell between them (Fig.3). In this study, perpendicular cutting was used to determine the shearing forces of silage corn (Kanafojiski et al., 1972; Sitkei et al., 1986; Persson et al., 1987; Chen et al., 2004).

Remark 1: as for the shearing test, a force-displacement curve was recorded up from the initial contact of the blade to the failure of the specimen, so the shearing energy was obtained using Eq.1.

$$W = \int_0^l F(x)dx \quad (1)$$

where:

W is the shearing energy required, [J]; l is the displacement from initial contact to shearing off the specimen, [mm]; $F(x)$ is the function of the shearing force-displacement curve, [N].

Materials

Silage corn, variety *Zhengdan 958* was used as test materials which was planted on May 1, 2020 and harvested in the middle of September 2020 from Experiment Station, Shandong University of Technology, Zibo. The fresh stalks with good growth and without holes, apparent cracks were selected. The moisture content of stalks on the test date ranged from 62% to 66% according to GB/T 1931-2009. The second section without node was selected as the internode specimen with a length of 90 mm–130 mm and the third node were selected as the node specimen with a length of 200 mm (Fig.4, 5).

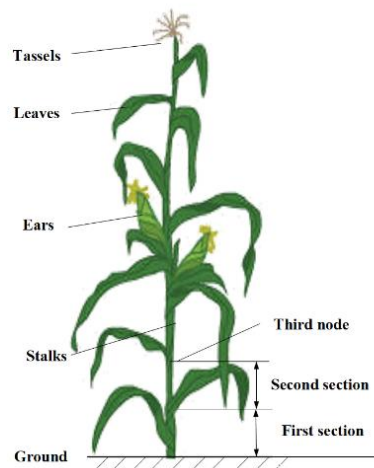


Fig. 4 -Sampling position



Fig. 5 - Partial specimens of silage corn stalk

The cross-section of stalks can be regarded as an ellipse (Igathinathane et al., 2006). The average dimensions of long axis (internode 24.5 mm, node 28.1 mm) and short axis (internode 18.8 mm, node 22.8 mm) were measured using digital calipers and the mean values were recorded. The compressing force and energy of the internode and node's short axis are higher than that of long axis in different loading forms including sing-point, direct pressure and three-point bending (Liu et al., 2014; Wang et al., 2010; Yan et al., 2020). Therefore, the short axis of specimens was selected as loading positions.

Compressing test

Fig. 6 shows examples of compressing processes in different loading directions. The shearing force and energy under different compressing rates and loading directions are the focus of our study (Zhao et al., 2010; Zhu et al., 2017).

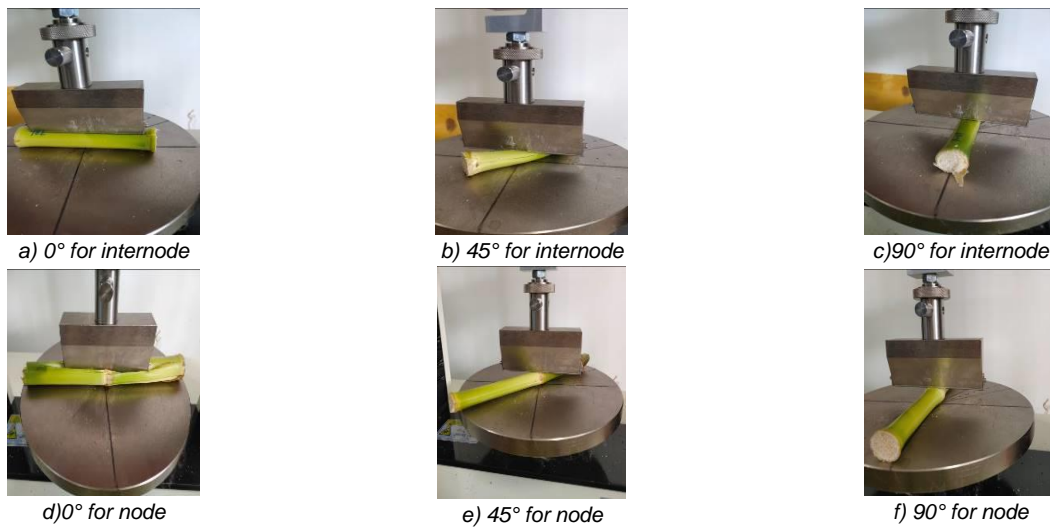


Fig. 6 - Compressing process for silage corn stalk specimen

The compressing rate is calculated using Eq.2,

$$\varepsilon = \frac{l}{d} \times 100\% \quad (2)$$

Where: ε is the compressing rate, [%]; l is the compressing displacement, [mm]; d is the diameter of the specimen at loading direction, [mm].

The compressing force increases at different growth rates by increasing the displacement respectively (Fig.7). On the stalk surface appears subsidence deformation and then cracks are produced at some point. However, the force-displacement curve of 0° is obviously different from that of other directions. Segment AB of 0° is the stage of extrusion deformation and the compressing force reaches its maximum values at point B, while the compressing rate is about 30%. The stalk epidermis is punctured with the compressing force larger than its damage strength. The compressing force correspondingly decreases quickly to point C, while the compressing deformation of the stalk core is dominant.

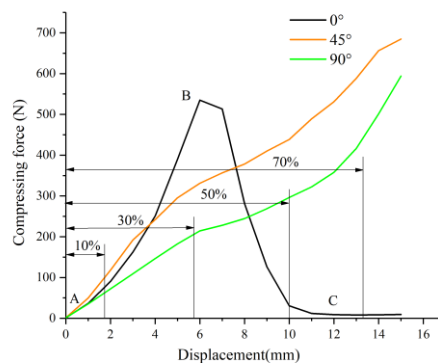


Fig. 7 - Compressing force versus displacement for internode of silage corn stalk

Fig. 8 shows that the heterogeneous morphology of stalks is the inner soft pith core covered with the thick tough skin. Based on direct observation, it was possible to identify three distinct regions to explain the deformation of the compressing process, which was similar to that of 45° loading direction.

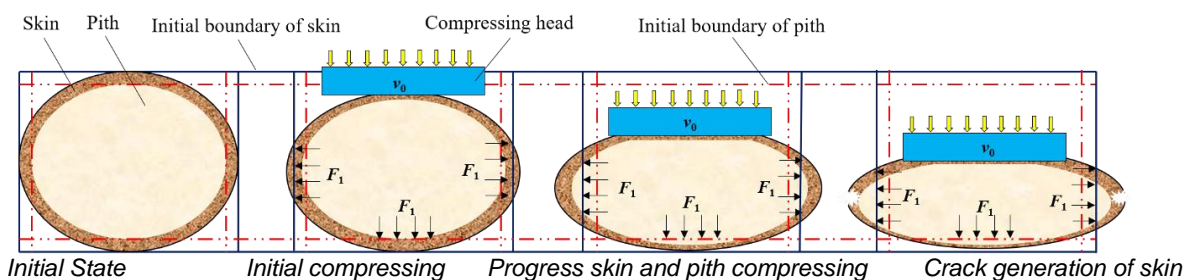


Fig. 8 - Compressing process of silage corn stalk internode in loading direction of 90°

Three distinct regions of 0° loading direction can also be identified to explain the deformation which was different significantly from the other two directions (Fig. 9).

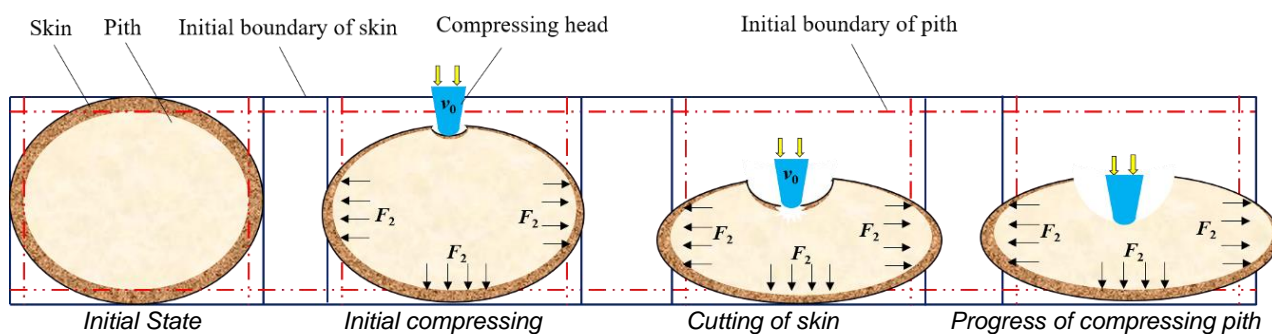


Fig. 9 - Compressing process of silage corn stalk internode in loading direction of 0°

Shearing test

This research emphasis is on the influence of the feeding mechanisms' operating parameters and shearing speed on shearing consumption, rather than chopping capacity and sectional form, although there are some evaluation indexes which are used to evaluate the effect of silage harvester, which might be one of the main points for our future studies.

The shearing process of internode and node were showed in Fig. 10.

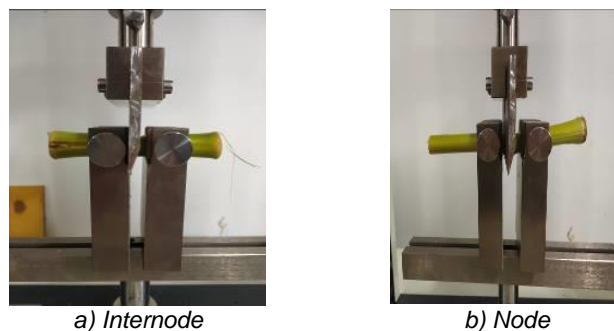


Fig. 10 - Shearing process for silage corn stalk specimen

Box-Behnken central composite experiment design

According to the previous study, the stalks showed obvious deformation with the compressing rate of 30%. Therefore, 10%, 30% and 50% were selected as different levels of compressing rates. The loading direction also had a significant effect on the deformation and force, especially at the direction of 0°. Various loading directions, selected for the shearing experiment were 0°, 45° and 90°. By referencing influences of cutter speed on corn straw for the minimum shearing force (Guo et al., 2016), the shearing speed was varied as 50, 100 and 150 mm/min. The Box-Behnken central composite experiment was adopted with three levels and factors. Each test group was repeated 3 times and their mean values, to reduce the random error, were applied as the final test result.

RESULTS AND DISCUSSION

In this section, the experiment data were processed using Design-Expert 8.0.6, the matching mathematical regression patterns were developed, the relation of salient factors was analyzed, the interaction of each factor was discussed and the parameters were optimized and validated.

Establishment of regression models and significance test

Table 1 presents the test results on the mean shearing energy of internode and node. The shearing energy for node is higher than internode (Zhu et al., 2017; Liu et al., 2014). Two quadratic polynomial response surface regression models for internode and node are shown as Eq.3 and Eq.4 respectively.

$$W_1 = 4.6 - 1.26A + 1.59B + 0.95C - 0.37AB - 0.44AC + 0.68BC + 1.51A^2 + 1.34B^2 + 0.47C^2 \quad (3)$$

$$W_2 = 8.19 - 0.92A + 1.24B + 0.83C - 0.015AB - 0.43AC + 0.64BC + 1.08A^2 + 0.99B^2 + 0.4C^2 \quad (4)$$

Table 1

Program and results of test quadratic rotation-orthogonal combination

NO.	Compressing rate (%)	Loading direction (°)	Shearing speed (mm/min)	Shearing energy (J)	
				Internode W_1	Node W_2
1	-1	-1	0	7.071	10.100
2	1	-1	0	4.827	8.095
3	-1	1	0	10.802	12.457
4	1	1	0	7.089	10.390
5	-1	0	-1	6.062	9.277
6	1	0	-1	4.874	8.482
7	-1	0	1	9.172	11.721
8	1	0	1	6.204	9.206
9	0	-1	-1	4.623	8.046
10	0	1	-1	6.618	9.407
11	0	-1	1	4.844	8.480
12	0	1	1	9.552	12.406
13	0	0	0	4.386	8.196
14	0	0	0	4.315	7.871
15	0	0	0	5.204	8.595
16	0	0	0	4.860	8.319
17	0	0	0	4.227	7.973

According to Table 2, on one hand, the p -value (< 0.0001) of the internode model indicated that the model was highly significant. The p -value (0.3932) of the “Lack of fit” indicated that no other major factors affected the indicators. The determination coefficient R^2 (0.9787) indicated that this model can explain more than 97% of the evaluation index. On the other hand, the p -value (< 0.0001) of the node model indicated that the model was also extremely significant. The p -value (0.6838) of the “Lack of fit” meant that no other major factors affected the indicators. The determination coefficient R^2 (0.9879) indicated that this model can explain more than 98% of the evaluation index. As a result, the model for internode and node can be used to evaluate the influence of the law of various factors on the shearing energy of silage corn stalks.

Table 2

ANOVA of regression model for shearing energy of internode and node

Source	Internode				Node			
	Sum of squares	Df	F-value	P-value	Sum of squares	Df	F-value	P-value
Model	63.08	9	35.70	0.0001**	37.66	9	63.54	0.0001**
A	12.78	1	65.12	0.0001**	6.81	1	103.36	0.0001**
B	20.15	1	102.63	0.0001**	12.35	1	187.37	0.0001**
C	7.21	1	36.74	0.0005**	5.45	1	82.65	0.0001**
AB	0.54	1	2.75	0.1414	9.610×10 ⁻⁴	1	0.015	0.9073
AC	0.79	1	4.03	0.0845	0.74	1	11.22	0.0122*
BC	1.84	1	9.37	0.0183*	1.64	1	24.96	0.0016**
A²	9.59	1	48.83	0.0002**	4.90	1	74.28	0.0001**
B²	7.56	1	38.50	0.0004**	4.14	1	62.81	0.0001**
C²	0.93	1	4.75	0.0656	0.68	1	10.35	0.0147
Residual	1.37	7	-	-	0.46	7	-	-
Lack of fit	0.67	3	1.29	0.3932	0.13	3	0.53	0.6838
Pure error	0.70	4	-	-	0.33	4	-	-
Total	64.46	16	-	-	38.12	16	-	-

Notes: **Parameter coefficient significant at a 99% confidence level; *Parameter coefficient significant at a 95% confidence level.

Guo (2016) carried on longitudinal shear characteristics properties experiment of dried corn straw and found that the influence of shearing angel on shearing force is greater than that of shearing speed, which is consistent with the experiment results in this paper. The optimized regression model after eliminating the insignificant factors in the interaction terms for internode and node are shown in Eq.5 and Eq.6 respectively.

$$W_1 = 4.8 - 1.26A + 1.59B + 0.95C + 0.68BC + 1.53A^2 + 1.36B^2 \quad (5)$$

$$W_2 = 8.19 - 0.92A + 1.24B + 0.83C - 0.43AC + 0.64BC + 1.08A^2 + 0.99B^2 + 0.4C^2 \quad (6)$$

Analysis of the effect of each factor on the response value

The degree of influence of each factor on the model can be reflected by the size of the contribution rate K -value, which is proportional to the size of the impact degree. The results (Table 3) showed that the sequence of contribution rate of loading direction, compressing rate and loading speed on shearing energy for internode was in decreasing order, while the compressing rate, loading direction and loading speed for node was in increasing order. The calculation methods are shown in Eq. 7 and Eq.8

$$\delta = \begin{cases} 0 & F \leq 1 \\ 1 - \frac{1}{F} & F > 1 \end{cases} \quad (7)$$

$$\begin{cases} K_A = \delta_A + 0.5(\delta_{AB} + \delta_{AC}) + \delta_A^2 \\ K_B = \delta_B + 0.5(\delta_{AB} + \delta_{BC}) + \delta_B^2 \\ K_C = \delta_C + 0.5(\delta_{AC} + \delta_{BC}) + \delta_C^2 \end{cases} \quad (8)$$

Where:

δ is the assessment value of F -value; K is the sequence of the contribution rate.

Table 3

Analysis of the contribution rate of each factor for internode and node					
Sample	Response values	Compressing rate	Loading direction	Loading speed	Contribution rate
Internode	Shearing energy	2.66	2.73	2.58	$B > A > C$
Node		2.43	2.46	2.83	$C > B > A$

Response surface analysis of internode

According to Table 3, the interactive item (BC) of the loading direction and loading speed had a significant effect on shearing energy for the internode ($p=0.0183$). The effects of the other interactive items were not significant.

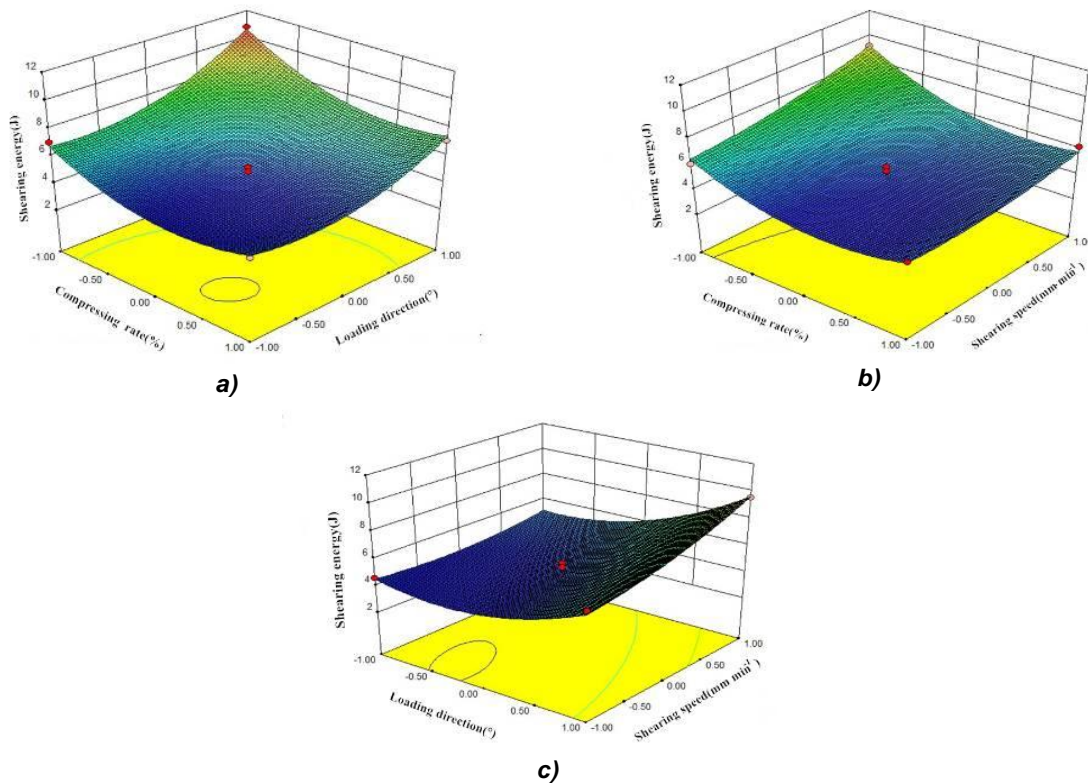


Fig. 11 - Influence of different factors on shearing energy for internode

Fig.11a showed that when the internode was compressed with the axis parallel or perpendicular to the compressing head, the effect of the compressing rate was a little greater than other orientation. Especially, the internode was split lengthwise with 0° loading direction and the internode became denser and easy to be cut while compressed to some extent. Therefore, the compressing rate was 50% and the loading direction was parallel to the compressing head, the shearing energy reached its minimum value (4.97 J). In this paper, the effect of the reduction rate is consistent with that of other radial compressing directions studied by other authors (Liu et al., 2014).

Fig.11b showed the shearing energy increased slowly with increase of the shearing speed (Zhao *et al.* 2010). When the shearing speed was high, the impact of the moving blade was the main reason for the increase in shearing energy. At the same time, the excessive impact caused the stalk to bend seriously and break away from the clamp. The shearing energy decreased gradually with the increase of the compressing rate. Therefore, it was helpful to reduce the shearing energy for internode by reducing the shearing speed and increasing the compressing rate. The effect of shearing speed on crop shearing strength and energy is consistent with Jiang's research (Jiang *et al.*, 2017).

Fig.11c showed the shearing energy changed little with the change of shearing speed at 0° loading direction, while the effect of the shearing speed was greater at 90° loading direction. When the shearing speed was high, the shearing energy increased rapidly with the loading direction from 0° to 90° loading direction. The epidermis of the internode was punctured at 0° loading direction. Therefore, the shearing energy of the soft pith was much less than that of the epidermis which was composed of cellulose and lignin, compressing at 0° loading direction before shearing was helpful to reduce the shearing energy. Igathinathane (2010) explained the nature of the cutting process of dried corn stalk by dividing the force-displacement into three identifiable regions. Deviation from the reported general force-displacement characteristics will occur due to the high moisture content of silage corn stalk, blade sharpness (Liu *et al.*, 2011).

Response surface analysis of node

According to Fig.12, the influence of experimental factors on the shearing energy of the node was similar to that of the internode. However, there were still some differences as the node was thicker than the internode for the material difference between internode and node.

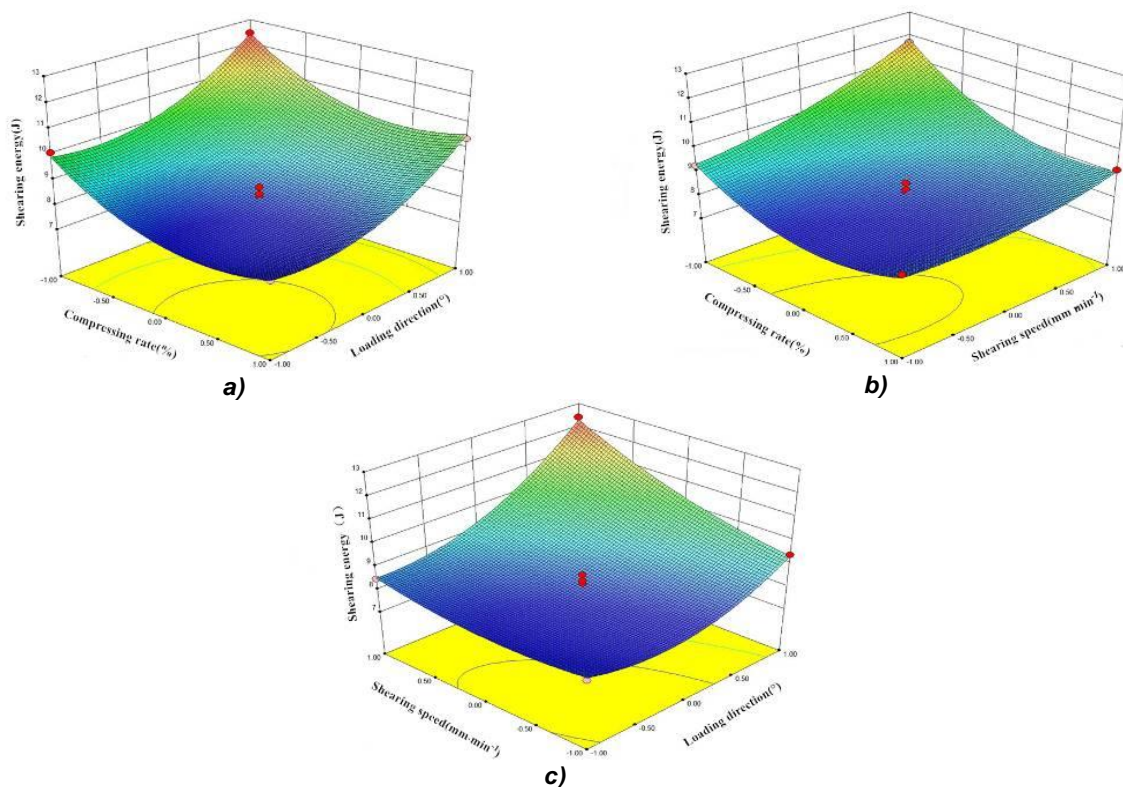


Fig. 12 - Influence of different factors on shearing energy for node

Fig.12a showed that the effect of the loading direction on shearing energy was greater than that of the compressing rate. The shearing energy was more easily affected by the compressing rate and decreased gradually with the increased compressing rate at 0° loading direction. At this time, the stalk epidermis was more easily damaged.

Fig.12b showed the interaction between the compressing rate and the shearing speed for the node was significant ($p < 0.05$). The effect of the compressing rate was greater than that of the shearing speed, *i.e.*, the shearing energy quickly decreased with the increase in compressing rate and increased with shearing speed.

Fig.12c showed the interaction between the shearing speed and the loading direction on shearing energy for the node was highly significant ($p < 0.01$). The shearing energy quickly rose with the increase in shearing

speed and the shearing energy reached its maximum (12.29J) at 90° loading direction with maximum shearing speed.

Parameter optimization and validation test

Based on the principle of low shearing energy consumption, the multi-objective optimization was carried out to obtain the optimal parameter combination of the compressing rate, the loading direction and the shearing speed, so the objective functions and constraints can be obtained as Eq.9,

$$\min W_1(A, B, C); \min W_2(A, B, C); -1 \leq A \leq 1; -1 \leq B \leq 1; -1 \leq C \leq 1 \quad (9)$$

It was concluded that the optimal parameter combinations were 36.08%, 25.4° and 73.39 mm/min. To verify the accuracy of the optimal results, ten parallel validations were carried out while the compressing rate, loading direction and shearing speed were chosen as 36%, 25° and 73 mm/min. It can be seen from the comparison of results (Table 4) that the experiment values were in good agreement with the theoretical optimal values and the relative error was both less than 4%, which confirmed that the optimized results were correct and credible.

Table 4

Comparison of average optimal and experimental value			
Project	Shearing energy for internode (J)		Shearing energy for node (J)
Optimal value	3.82		7.55
Average experimental value	3.97		7.81
Relative error/%	3.95		3.43

CONCLUSIONS

1. From the compressing test, the compressing force increased with increasing the displacement respectively at loading direction of 45° and 90°, while the compressing force decreased sharply as the compressing head pierced the epidermis of the silage corn stalk at 0° loading direction. This lower strength of the silage corn stalk at the loading direction of 0° can be exploited advantageously to develop feeding mechanisms.

2. From the Box-Behnken central composite experiments, the overall shearing energy consumption for shearing off the node was higher than that for internode due to different structural properties. The significant effects on shearing energy in a decreasing order was the loading direction, compressing rate and loading speed for internode and the loading speed, loading direction and compressing rate for node. The optimal parameter combinations were 36.08%, 25.4° and 73.39 mm/min.

3. In general, compressing the silage corn stalk to some extent before shearing at 0° loading direction and lower shearing speed were beneficial to saving energy during the process of shearing off the silage corn stalk. The reduced energy requirements of the silage corn stalk could be exploited advantageously to present new reference for the feeding and cutting mechanisms of silage harvester.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research and Development Program, China (Grant No. 2016YFD0701302), Key Science and Technology Innovation Project of Shandong Province, China (Grant No. 2019JZZY020615)

REFERENCES

- [1] Chattopadhyay, P., & Pandey, K. (1999). Effect of the blade and operational parameters on energy requirement in flail forage harvesting. *Agricultural Engineering Research*, 73(1): 3–12.
- [2] Chen, Y., Chen, J., Zhang, Y., & Zhou, D. (2007). Effect of harvest date on shearing force of maize stems. *Livestock Science*, 111(1): 33–44.
- [3] Chen, Z., Wang, D., Li L.Q., & Shan R. (2012). Experiment on tensile and shearing characteristics of rind of corn stalk. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 28(21): 59–65.
- [4] Cheng, H., Jiang, F., Liu, D., Song, H., & Song, E. (2019). Current situation, existing problems and countermeasures of production and application of whole corn silage in Shandong province (山东省全株玉米青贮生产与应用现状、存在问题及对策). *China Cattle Science*, 45(6), 32–34.
- [5] Guo, Y., Cheng, Y., Ben, D., Yang, J., Wang, B., & Dong, L. (2016). Experiment of longitudinal shear

- characteristic properties of corn straw (玉米秸秆纵向剪切特性试验). *Journal of Chinese Agricultural Mechanization*, 37(2): 123–126.
- [6] Ighathinathane, C., Womac, A. R., & Sokhansanj, S. (2010). Corn stalk orientation effect on mechanical cutting. *Biosystems Engineering*, 107(2): 97–106.
- [7] Ighathinathane, C., Womac, A., Sokhansanj, S., & Pordesimo, L. (2006). Mass and moisture distribution in aboveground components of standing corn plants. *Transaction of the ASAE*, 49(1): 97–106.
- [8] Jiang, M., & Guo, Z. (2017). Effects of vertical pressure and shear velocity on direct shear strength and dilatancy properties of wheat (竖向压力和剪切速率对小麦直剪强度及剪胀特性的影响). *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 33(6): 275–280.
- [9] Lan, J., Pan, B., Wang, B., Li, L., & Zhang, R. (2019). Analysis on current situation of silage maize quality in Northeast China (东北青贮玉米品质现状分析). *Heilongjiang Agricultural Sciences*, (10), 95–99.
- [10] Li, Y., Qin, T., Chen, J., & Zhao, Z. (2011). Experiments and analysis on mechanical property of corn stalk reciprocating cutting (玉米秸秆往复切割力学特性试验与分析). *Transactions of the Chinese Society of Agricultural Engineering*, 27(1): 160–164.
- [11] Liu, L., Bing, Y., Dong, X., Ai, M., & Yang, X. (2014). Effects of loading conditions on cracks of corn stalk and power consumption of machine (玉米秸秆压缩加载条件对其裂纹和机器功耗的影响). *Transactions of the Chinese Society of Agricultural Engineering*, 30(3), 163–169.
- [12] Lu, Y., Payen, S., Ledgard, S., Luo, L., & Zhang X. (2018). Components of feed affecting water footprint of feedlot dairy farm systems in Northern China. *Journal of Cleaner Production*, 183: 208–219.
- [13] McRandal, D., M., & McNulty, P. (1980). Mechanical and physical properties of grasses. *Transactions of the ASAE*, 23(4): 816–821.
- [14] Wang S., Du, J., Zhao, L., Jiao, L., Li, Z., & Xue, Z. (2019). Tensile and shearing strength properties of the stems of king grass (王草茎秆拉伸与剪切的强度特性). *Chinese Journal of Tropical Crops*, 40(6): 1188–1194.
- [15] Wang, G., Wang, D., Tabil, L., & Opoku, A. (2010). Shearing strength of timothy grass stem. *ASABE Annual International Meeting*. June 20–June 23, 2010 1009362. (doi:10.13031/2013.29861).
- [16] Yan, E., Wang, Z., Han, B., Xu, B., Chen, Y., & Qi, Z. (2020). Effect of water content and cutting sliding angel on straw cutting power consumption (含水率及切割滑切角对秸秆切割功耗影响规律). *Agricultural Mechanization research*, (2): 162–167.
- [17] Zhao, Z., Li, Y., Xu, L., & Song, S. (2010). Experiment on cutting mechanical property of single super rice stalk (超级稻单茎秆切割力学性能试验). *Transactions of the Chinese Society for Agricultural Machinery*, 41(10): 72–75.
- [18] Zhu, Z., Zhang, K., Li., & Zhang, H. (2017). Study on mechanical properties of corn stalk (玉米秸秆机械性能研究). *Jiangsu Agricultural Science*, 45(12): 178–181.